

# Non Nuclear Testing of Reactor Systems In The Early Flight Fission Test Facilities (EFF-TF)

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**Abstract** – *The Early Flight Fission-Test Facility (EFF-TF) can assist in the design and development of systems through highly effective non-nuclear testing of nuclear systems when technical issues associated with near-term space fission systems are “non-nuclear” in nature (e.g. system’s nuclear operations are understood). For many systems, thermal simulators can be used to closely mimic fission heat deposition. Axial power profile, radial power profile, and fuel pin thermal conductivity can be matched. In addition to component and subsystem testing, operational and lifetime issues associated with the steady state and transient performance of the integrated reactor module can be investigated. Instrumentation at the EFF-TF allows accurate measurement of temperature, pressure, strain, and bulk core deformation (useful for accurately simulating nuclear behavior). Ongoing research at the EFF-TF is geared towards facilitating research, development, system integration, and system utilization via cooperative efforts with DOE laboratories, industry, universities, and other NASA centers. This paper describes the current efforts for the latter portion of 2003 and beginning of 2004.*

## I. INTRODUCTION AND BACKGROUND

Despite the relative simplicity and tremendous potential of space fission systems, the development and utilization of these systems has proven elusive. (Houts, 2000). Because nuclear testing is expensive and labor intensive, it is likely that actual nuclear testing of systems would not occur until late in the development stage, or even validation stage, of a reactor system life cycle. If one could thermally hydraulically test the systems by mimicking the heat from fission, then evaluation could begin very early in the life-cycle, flushing out issues and validating designs long before the first nuclear test on the same system is carried out. The purpose of the Early Flight Fission Test Facilities (EFF-TF) is to give high confidence in thermal hydraulic performance of fission systems through a series of prototypic non-nuclear tests. This provides risk mitigation very early in the program for a variety of reasons:

- It separates paper reactors from real reactors. In the conceptual design phase, all reactors start as a highly functional idea on paper. It is not until the systems are in fabrication and test when one can prove that the idea is really technically feasible. Non-nuclear testing forces issues related

to thermal and stress performance, manufacturing capabilities, and integration procedures to come to light quickly. It also serves as a forerunner to determine the cost of fabrication of each system, without fuel, very early in the design phase.

- Implementing a hardware focus (non-nuclear tests) early in the design phase drives designers and fabrication engineers to provide reasonable layouts that can be successfully manufactured and meet defined operating requirements. This ensures that the design of the reactor has a foundation built on hardware experience rather than analysis alone. Changes made to the design are based on experimental data.
- Non-nuclear testing early in the design phase serves as a method to validate not only reactor concepts, but associated sub components (e.g. heat exchanger concept, high temperature valves, pumps, etc...) and manufacturing processes for these components and their integration into the system (e.g. brazing, Hot Isostatic Pressing, Electron Beam Welding).
- Non-nuclear testing early in the design phase can allow resolution of issues upfront (e.g. designers discover issues and make changes before final

design), or identifies “tall tent-poles” that must be resolved prior to a final design decision.

- Non-nuclear testing provides a mechanism for the verification of analysis, specifically, thermal, stress, energy balance models, and CFD codes.
- Non-nuclear testing serves as a precursor to verify that appropriate documentation is generated/exists for integration, validation, and verification of the systems. This includes: verification of assembly processes, verification of safety processes (e.g. related to handling liquid metals), verification of start-up sequence (e.g. potential thermal constraints), and verification of form, fit, and function to name just a few.
- Non-nuclear testing allows for margin testing investigating off-nominal configurations and conditions. Because no fuel is involved, different configurations of a reactor system can be readily changed and retested – in some cases with a single day turn around. This provides relevant, timely, and inexpensive data, which performance engineers can rapidly filter back into the design process, ultimately turning out a more robust component.
- Non-nuclear testing is a logical portion of the system development path. If the system is designed to be testable via non-nuclear methods, then great confidence in regards to the thermal hydraulic performance is established long before the actual nuclear test or flight qualification testing begins.
- Non-nuclear testing provides a mechanism to initiate thermal hydraulic lifetime testing, and in some cases, accelerated lifetime testing very early in the design phase.
- If non-nuclear testing is carried out early in the design phase, then the reactor systems themselves can serve as a test bed for the development of state of the art instrumentation. For example, high temperature measurement systems and high temperature strain gages.
- Non-nuclear testing offers the ability to perform multiple tests on the same piece of hardware. For example, the same system can easily be move between tests (e.g. subjected to vibration testing, thermal hydraulic tested, and if desired, moved back to vibration testing)

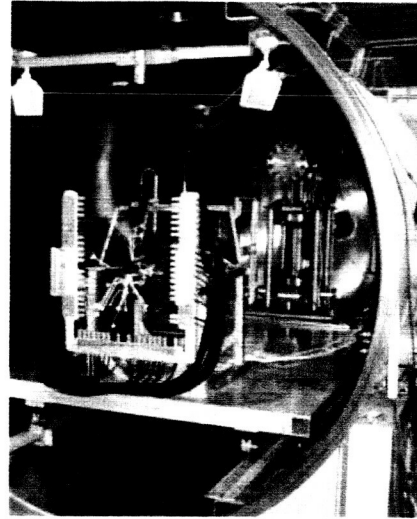
In order to maximize the benefits of a strong non-nuclear testing program, tangible realistic prototypic hardware milestones must be shown on a yearly basis. The Early Flight Fission - Test Facilities (EFF-TF) demonstrates that a progression of successful non-nuclear

tests, each building on the achievement of its predecessor provides applicability to the next system. The Module Unfueled Thermal-hydraulic Testing (MUTT) successfully demonstrated the use of resistance heaters to realistically simulate heat from fission – verifying both energy transfer capability and heat pipe operation even under extreme operating conditions (fast startup and exposure to air) (Van Dyke, 2000). Because the heat transfer within the Safe Affordable Fission Engine (SAFE) 30 (30 kWt thermal class reactor) system is highly predictable, the SAFE-30 and SAFE-30 end-to-end demonstrator test programs provided experimental data to anchor computational models. The models were then used to predict the temperature and heat transfer within the core, along the heat pipes and into the energy conversion cycle. These data were used as a research tool supporting the development of a larger core design. The SAFE-30 tests also provided an overview of the general techniques, environments, and hardware used to simulate the heat transfer within a nuclear core. Later tests that incorporated a Stirling engine with the SAFE-30, demonstrated that a heat pipe power system is a relevant design and could provide power for future space applications. (Hrbud, 2002). Initial results indicate that the system model was able to predict behavior, even when subjected to less than textbook test conditions, demonstrating the overall capability of the heat pipe system. (Poston, 2002).

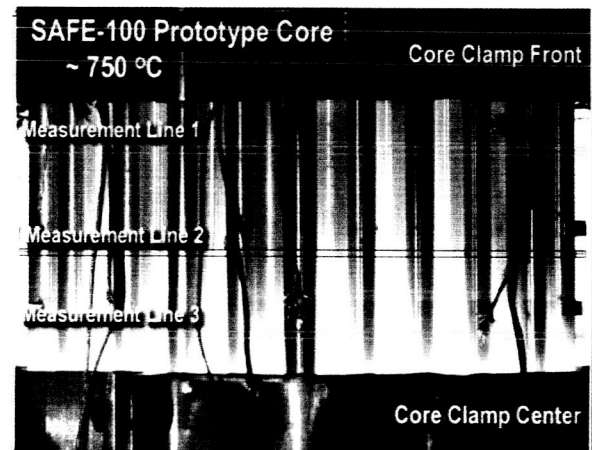
Building on the successes of the SAFE 30 test program, the EFF-TF has expanded its capabilities to include designing, fabricating and/or testing of three unique reactor systems while simultaneously making modifications to the facilities and developing state-of-the art instrumentation techniques. By February of 2003, the EFF-TF capability had grown from testing at the module level in a single 2 ft. diameter vacuum chamber to a capacity to perform full-scale design, fabrication, and testing in 3 unique facilities at MSFC (Van Dyke, 2004). These facilities have been established for the sole purpose of simulating performance of near term space fission systems. Emphasis for the 2003 calendar year was on the development and fabrication of a 100 kW class heat pipe reactor (SAFE 100 and SAFE 100a), which included a prototype heat exchanger, the assembly and testing of gas cooled reactor concept, and the design of a proof-of-concept pumped liquid metal system (flow loop). Since many of the capabilities developed at the EFF-TF are applicable to multiple concepts, significant effort was placed on developing several state-of-the-art instrumentation techniques; approaches that provide improved data for both benchmarking codes and controlling power feed back loops to more closely simulate a nuclear systems response.

## II. THE TEST FACILITIES

Full scale testing of all reactor concepts is performed in a 9 ft diameter (18 ft barrel length with elliptical domes) vacuum facility (Figure 1). This chamber, driven by 4 diffusion pumps (32,000 l/s each) and 3 roughing pumps (34,000 l/min each), can achieve an ultimate vacuum level of  $10^{-7}$  torr or better. Power is provided to the test article via an automated 32-zone power and control system, which provides the capability of a simulating a reactivity/dimensional-change/power loop for systems where reactivity feedback is dominated by core deformation. The simulation was accomplished by using nuclear analyses (or possibly criticality experiments) to establish the reactivity worth of various core deformations. When a core deformation is measured, the reactivity worth is assessed (based on previous calculations / experiments), and the core power profile adjusted accordingly via kinetics calculations. To demonstrate this closed feedback loop, a geometric prototype of a SAFE-100 kWt class heat pipe reactor (blank tubes— no heat pipes for power removal) was used. The EFF-TF simulated slow to moderate transients on this setup (e.g. reactor startup) while realistically taking into account the dominant reactivity feedback mechanism (core deformation). In order to provide accurate deflection measurements, a 6.3-megapixel high-resolution camera was used to image the core (Figure 2). The deflection was calculated using an elaborate algorithm that counted pixels recorded on a linear scan of a core cross section. To improve both performance and control, the SAFE-100 core was rewired for 9 control zones. In addition, a calibration procedure was established for the high-resolution camera to account for deformations in the vacuum chamber and view port (during the vacuum down phase). After the first several checkout tests were completed to verify the systems (power and camera) were “talking” to each other, a sensitivity analysis on deflection measurement accuracy vs. reactivity value was completed. Results indicated that the deflection measurement resolution was well within the range needed to demonstrate closed loop reactivity feedback. Future work includes a change out the power control hardware (taking the system from communication via serial cable to network), and optimization of the control code.



**FIGURE 1.** 9 ft vacuum chamber with 2 reactor concepts installed for testing.



**FIGURE 2.** High-resolution image of core during test

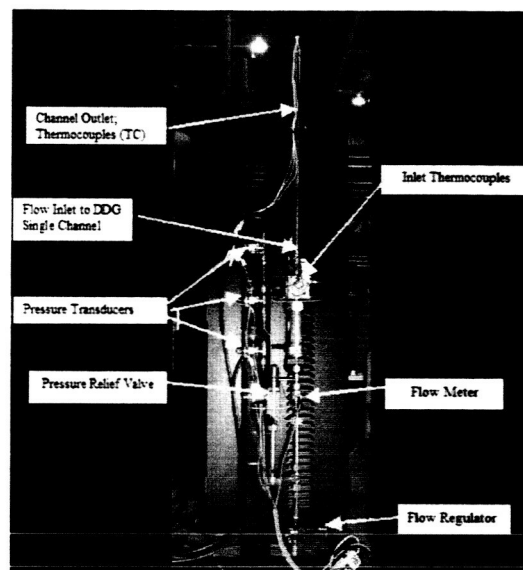
Another state-of-the art instrumentation technique demonstrated this past year was the use of an optical fiber “probe” to measure both temperature and strain. Through the use of a distributed sensing system (DSS) based on fiber Bragg grating technology licensed by Luna Innovations (manufacturer of the optical probe system) from NASA Langley, Luna was able to show a 3-D axial temperature profile in a core interstitial region of the heat pipe reactor concept. The fiber, not much larger than a human hair, was inserted into an interstice between 3 “fuel” tubes. While the fiber has the capability of sensing a temperature every centimeter along its length (axial length of the core), for the purposes of this proof-of-concept test, a temperature measurement was taken every 2 centimeters. During test the fibers were subjected to temperatures in excess of 800 °C. The data measured by the fibers closely match the data measured by strategically placed type-K thermocouples. With the success of the

fiber optic temperature evaluation, a second test using the optical fibers to measure strain along a “fuel” tube and strain around the core perimeter-retaining bracket was conducted. Although the test was restricted to a maximum of 250 °C (limitations of the bonding agent), the strain data measured by the probe closely matched the theoretical strain data calculated for 316 stainless steel. These tests were performed on the same geometric prototype SAFE-100 core as described above in the deflection-reactivity-power feedback loop experiment. While this demonstration was performed on a heat pipe reactor concept because of ease to access the reactor, it can be applied to every reactor concept tested at the EFF-TF.

Every reactor concept tested in the EFF-TF requires heat removal during operation (e.g. gas heat exchanger on the heat pipe module reactor concept and gas flow through the direct drive gas reactor concept). The engineering design for a closed loop gas conditioning system (Helium/Argon mixture) was completed and components procured during 2003. However, due to the long lead-time high-pressure gas compressor (approximately 1 year), current testing of all reactor concepts in the EFF-TF utilize a single pass gaseous nitrogen flow (provided by high pressure facility system). Using the nitrogen flow maintains program momentum and allows for core assembly validation (e.g. integration) and a method to begin benchmarking codes.

A single channel gas flow apparatus was constructed to make flow measurements and validate predictive codes (thermal, energy balance and CFD) to be used on both the DDG and SAFE-100a heat exchanger. The DDG channel setup (see figure 3) was evaluated prior to embarking on full-scale system tests. The experimental apparatus was originally constructed for ambient exit conditions without preheating the inlet gases, however, requirements quickly grew necessitating that test conditions match those expected for the “full test article”. Specifically, the capability to measure a pressure drops of less than 7.5 psid in the annulus test region, maintain an exit pressure of 150 psia, and meet a temperature difference of 200 °C across the channel. A LabVIEW program was written to control power and flow in addition to perform the data acquisition function. Data recorded during these single channel tests resulted in changes to the 37-pin DDG flow path design (influenced the flow regime along the fuel clad). The single channel results were implemented in the assembly in the full 37-pin system. Following the completion of DDG channel tests, the single channel test setup was modified to accept an element from the SAFE-100a heat exchanger; tests were underway in early 2004. Data collected from these evaluations helped facilitate a rapid assessment of hardware configurations and

operating flow conditions. In addition, it provided early data for validation of CFD codes and energy balance models (used to predict the behavior of the core hardware to be tested in the 9 ft vacuum chamber).

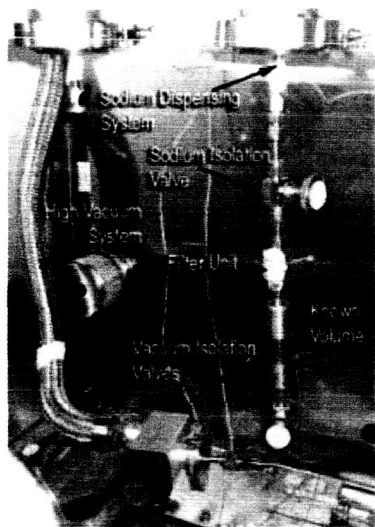


**FIGURE 3.** Single Channel Test Apparatus

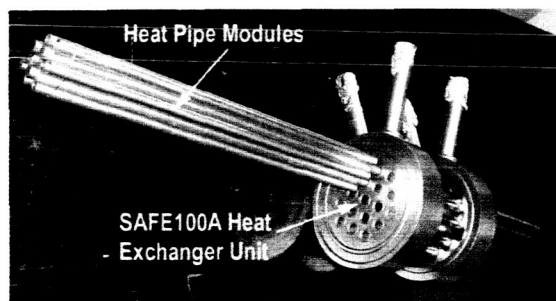
Two of the three reactor system concepts being tested in the EFF-TF require expertise in handling alkaline metals (e.g Sodium for heat pipes and Sodium-Potassium mix (NaK), Sodium or Lithium for liquid metal concepts). The liquid metal handling machine (glove box system equipped with dry-cool and ni-train units) was assembled, providing a capability to build this expertise. While the machine capabilities were first demonstrated by filling heat pipe modules with sodium, the experience gained is applicable to all concepts utilizing alkaline metals. Using stainless steel heat pipe modules (designed for the SAFE-100), a fill process was developed, optimized, and validated. A total of 25 stainless steel heat pipe modules were successfully filled with sodium. Each module was designed for, and received, approximately 35 grams of liquid sodium metal dispensed under the inert dry argon glove box atmosphere (maintained at < 1 ppm oxygen and < -75 °C dew point). In addition to performing the fill, each of the heat pipe modules was vacuum processed, closed out via hermetically sealing with a TIG welder, “wet-in” using a high temperature furnace, and acceptance tested at approximately 700 °C. Final metrology and radiography data collected on several of the completed modules verified the fill process had no effect on the modules geometry (as anticipated). In addition to using these modules for core and HX testing, the heat pipes also be used in accelerated life testing (per setup criteria from the Los Alamos National Laboratories). Figure 4 shows the fill machine and internal calibrated cylinder. Figure 5



shows the completed heat pipe modules arranged in a core assembly with a representative HX.



**FIGURE 4.** Calibrated Cylinder In the Fill Machine



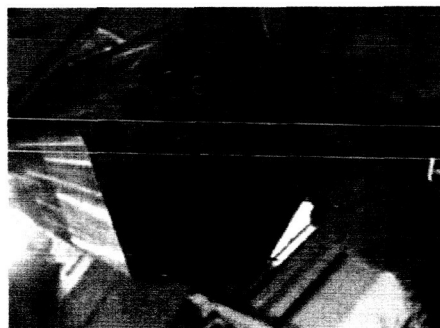
**FIGURE 5.** Heat Pipe Modules Assembled in Core Like Configuration For Test.

Because the EFF-TF mission is to evaluate multiple reactor concepts (heat pipe, gas cooled, and liquid metal), each with its own unique requirements for testing (e.g. core geometry, temp, duration, etc.), the development of thermal simulators and thermal simulator/core integration is a continual process in optimization. Accomplishments during 2003 included:

- Updated design for the connecting thermal simulators (e.g. eliminating the copper coupler block) for the SAFE 100a.
- Research into the use of carbon composites or braided carbon fibers.
- Developing spiral wound elements.
- Design of a graphite element that is "sealed" with gaseous Helium to better simulate pin conductivity as well as isolate the "heater" from the core (addressing possible material "contamination" issues).

#### IV. GAS COOLED REACTOR TESTING

Engineers at Sandia National Laboratories devised a "testable" gas cooled reactor concept that was cooled by a noble gas mixture of helium and xenon (Wright and Lipinski, 2003). This system, termed the Direct Drive Gas (DDG) cooled concept makes use of a LANL baseline design with a primary objective to demonstrate that the gas-cooled reactor is a testable concept using non-nuclear methods. While assembly of this core proved to be slightly more challenging than the assembly of the modular heat pipe cores, successful assembly and integration of a 37-pin concept demonstrated that a core of this type could be assembled and tested using non-nuclear methods. Figure 6 shows heater insertion into the monolith core block and figure 7 show assembly of the core within the gas "bonnet" structure



**FIGURE 6.** Heater placement on 37 pin DDG.



**FIGURE 7.** Integration of 37 pin core into gas "bonnet" structure. Note gas entrance plenum into core at the top of the structure.

By the end of 2003, integration of the DDG into the 9 ft vacuum chamber was finished and the first test matrix using GN<sub>2</sub> completed. While the data followed the heating profile "trend" as the analysis had predicted, the fidelity in the pressure instrumentation was too "rough" and the data

was unable to validate the code predictions. New pressure gages have been installed and testing is expected to be complete by the end of March 2004.

### HEAT PIPE REACTOR TESTING

With the success of previous tests using heat pipe reactor systems (reference SAFE 30 TM here), the focus for this particular concept during 2003 was on matching performance data with higher fidelity as well as continuing the investigation of manufacturing techniques for fabricating both core modules and heat exchanger. For example, this year, all of the core modules were successfully fabricated using a hot isostatic pressing (HIP) technique. This includes both stainless steel and Nb1Zr modules. Validation of the process for fill and closeout of heat pipes was demonstrated and a lifetime testing facility for heat pipe modules was constructed. Design and fabrication of a prototypic heat exchanger using gas as the transfer medium (removing heat from the heat pipes) was concluded and the heat exchanger is currently being installed on a heat pipe reactor. Finally, in an effort to match the thermal effects of pin conductivity (between the pin and clad), a sealing face structure is being designed and fabricated. If successful, this would allow for a non-obtrusive method of "flooding" the core (e.g. fill gaps between clad structure and thermal simulator) with helium, while not compromising the test article geometry or power control hook-up.

The SAFE-100 stainless steel reactor core design, which includes a prototypic heat exchanger, was provided by LANL. This reactor is comprised of 61 identical heat pipe modules. Each module is a tri-lobe structure, with a central heat pipe attached to three fuel pins. The 61 modules are nested together to form the core array. Heat generated in the core fuel pins is conducted to the heat pipes, which in turn transfer the heat energy to heat exchangers that are brazed in place. The heat exchanger is a monolithic axial flow design, with the coolant gas flowing through annular passages around the clad "jacketing" the heat pipes. Because of budgetary constraints, a partial core (SAFE 100a), which consists of the internal 19 modules of the SAFE 100 and accompanying heat exchanger were fabricated for testing in the EFF-TF. Even though a full SAFE 100 core is not scheduled to be tested, the data from the SAFE 100a will be useful in validating thermal, stress, and CFD models used in the designs of all heat pipe cores. Because the core is modular in nature, the performance of one module depends wholly on heat transfer within the module and between this module and immediately adjacent modules. Thus, the inner 7 modules in the SAFE 100a are completely representative of the inner 37 modules of the SAFE 100. The performance of the modules at the

core/side reflector interface is affected by heat transfer to the side reflector. This is simulated by sizing the thickness of the insulation so that the heat flux at the core/reflector boundary during test is equal to that calculated in the reactor. Not only can the codes be validated with this data, but the manufacturing techniques, integration processes and performance of the HX concept will also be validated. Even with a partial core, this testing will provide verification of assembly processes, verification of safety processes (related to handling alkaline metals), verification of start-up sequence (thermally), and verification of form, fit, and function of the heat pipes with HX.

While the SAFE 30 successfully demonstrated the ability to braze a module, the SAFE 100a demonstrates the ability to form modules using a HIP technique. This technique adjoins 3 stainless steel fuel tubes around a central heat pipe with filled interstices between the heat pipe and the clad structure of the 3 adjoining "fuel" pins. If fabricated successfully, from a thermal and stress standpoint, the module appears as though it were fabricated from a single piece of material (e.g. gun drilled). There should be no voids in the interstices material and no stress "weak points" at the adjoined tubes due to manufacturing processes. This technique was also successfully demonstrated for Nb1Zr (figure 8).

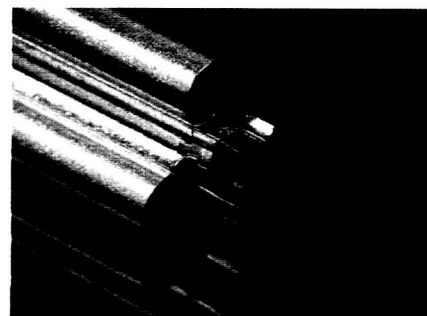


FIGURE 8. HIPPED Nb1Zr module

The heat exchanger for the SAFE 100a is a monolithic, annular flow design selected both for simplicity of fabrication and for good thermal-hydraulic performance. Although it is constructed from stainless steel 316L, it's geometry, flow conditions, and fabrication techniques are based on the SAFE 100 (stainless steel) and SAFE 400 (refractory metal) designs. The unit has been proof tested and mounted over the condenser ends of the SAFE 100a heat pipes that extend out from the core. While the assembly gaps between the heat pipes and the heat exchanger were designed to be brazed to the heat pipes, initial tests will fill the gaps using gaseous helium to allow for maximum heat transfer. Figure 9 shows a cut-away view of the heat exchanger and figure 10 shows the finished part assembled on the SAFE 100a core. Flow

enters the heat exchanger at the top set of tubes closest to the core, passes into a flow distribution ring and crosses into the upper plenum. The flow traverses down 19 separate annular flow passages (1 passage per heat pipe). The flow exits the annular flow passages and recombines in the lower plenum, where it crosses back into the lower flow distribution ring and finally into the coolant returns line.

To accommodate the changes in the heat exchanger (between the SAFE 100 and SAFE 100a designs), the dimensions of the inlet and exit flow geometry were **adjusted to provide approximate flow similarity between the 19-module test concept (SAFE 100a) and the 61-module reactor concept (SAFE 100)**. Flow annulus width and length were sized to meet design requirements (DP/P, T-core, etc.) and to optimize weight vs. temperature. The inlet/exit plenums were designed to minimize pressure drop and provide good flow distribution. The tube and exterior wall thicknesses were sized to meet structural requirements, and all welds are full penetration e-beam welds to demonstrate the fabrication process could be used for a refractory metal HX if desired. The sleeve dimensions are varied with heat pipe power to produce the same temperature delta in the coolant in each channel. The flow areas in the inlet/exit pipes, flow distribution rings, and plenums were reduced in the 19 module design to maintain the same ratio of flow areas in these passages to that in the flow annuli of the 61 module design. This approach was taken to maintain the distribution of Reynolds numbers, pressure drops, and heat transfer coefficients through the 19-module heat exchanger approximately the same as in the 61-module design. Single channel testing was completed to validate flow characteristics, specifically to assess pressure drop and uniformity of flow distribution prior to full scale testing. Data from the 19 heat pipe testing will be used to validate the analysis for pressure drop and flow distribution in the heat exchangers for the SAFE 100 and SAFE 400 designs.

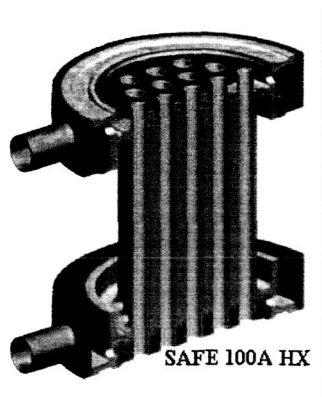


FIGURE 9. Cut-away view of SAFE 100a HX

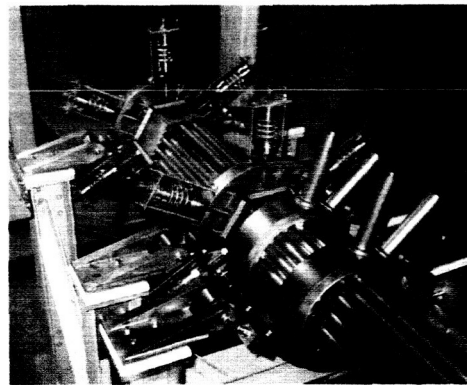


FIGURE 10. HX on the SAFE 100a core.

### LIQUID NAK REACTOR CONCEPT

With the successful demonstration that a realistic test of a heat pipe reactor core and a direct drive gas cooled core concept is viable, the EFF-TF began work on a liquid metal reactor concept. The goal of this first liquid metal system is to demonstrate the ability to pump a liquid metal in representative loop geometry. NaK was selected for the initial system due to the ease of handling (liquid at room temperature); the flow loop is also compatible with sodium, and lithium to an extent (lower operating temperature due to nickel solubility issues). The general hardware components for this first system include: a NaK core assembly, NaK/GHe heat exchanger, liquid metal pump, expansion tank and ancillary instrumentation items such as thermocouples, liquid level sensor and flow meter.

The proposed plan is to design and fabricate the NaK core assembly based on a 100 kWt NaK core concept study performed by the Los Alamos National Laboratory. The design, fabrication and test approach taken is patterned after that pursued for the DDG 37 pin concept; namely reducing the number of core fuel pins in the test unit to approximately 1/3 of the total, saving both cost and fabrication time. Figure 11 illustrates the selected design for the core concept, which uses annular fuel pins and two-pass coolant flow. The coolant enters the core through an annular inlet plenum (positioned at the top) that directs it into a circumferential flow passage formed between the outer shell and core block. The flow follows this perimeter passage traversing the length of the core and exiting into the lower manifold. This manifold distributes the coolant for a return trip to the top of the core via annular gaps formed between the fuel pins clad and core block. At the top of the core an outlet plenum collects the heated NaK. The electromagnetic pump procured for this project is a Mine Safety Appliance Style

VI unit capable of delivering 30 gpm at 20 psig, illustrated in figure 13. Other hardware such as valves and instrumentation are being procured while the team finalizes fabrication drawings and procedures for the test setup.

The NaK flow loop shall be laid out on a portable frame structure (similar to other experiments) simplifying installation in the EFF-TF vacuum chamber. The initial concept orientation of components is illustrated in figure 14. The focus of this project is to keep the flow loop simple so that experience can be gained by rapidly fielding a system that can be easily tested. The main component of this system that is prototypic is the NaK core assembly, the reminder of the system serves as a "test bed" (components not prototypic of flight). Once operational, this system provides an excellent platform that can be adapted to test specially designed components (heat exchangers, pumps, alternate core assemblies, etc.) that are more prototypic of flight type units. These specialized devices can be integrated into the loop and evaluated at various temperature and flow conditions (within the operating bounds of the stainless steel system). The system plumbing and components for this initial work are not equipped with heaters since NaK is a liquid at room temperature. Interesting future work could make use of sodium to look at freeze/thaw issues. To fill and operate this flow loop with sodium shall require heater traces on all components so that complete filling of the system is possible (no freeze points). These operations would also be applicable to lithium, however maximum operating temperature is again lower due to lithium/stainless steel compatibility issue.

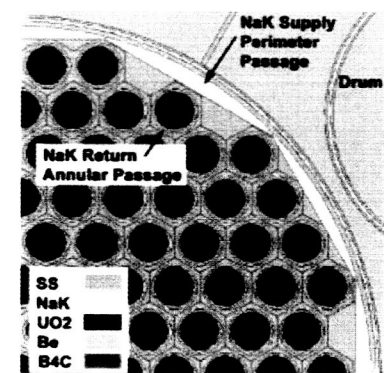


FIGURE 11. NaK Core Flow Paths

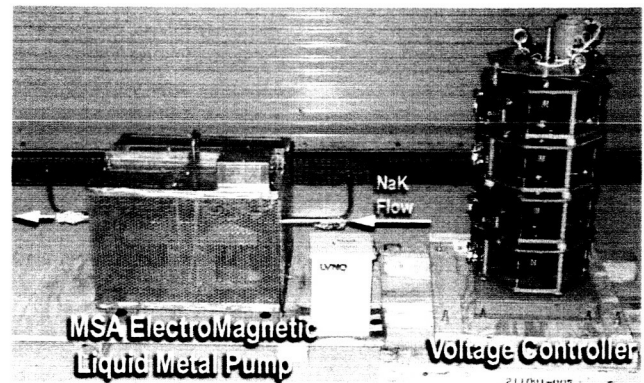


FIGURE 12. EM Pump layout

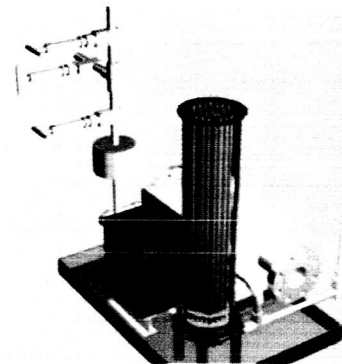


FIGURE 13. NaK system Layout

## SUMMARY

High confidence in fission system performance can be attained through a series of non-nuclear tests. In order to maximize the benefits of a strong non-nuclear testing program, tangible realistic prototypic hardware milestones can be shown on a yearly basis. The SAFE series demonstrated this via testing of the SAFE 30, SAFE 100 prototype, and the SAFE 100a. The direct drive gas (DDG) cooled reactor built upon the successes of the SAFE program (e.g. how to make and wire thermal simulators), and the liquid metal reactor system will use the experience learned in the assembly and testing of the DDG. The progress made in the EFF-TF demonstrates that each product must build on the success of its predecessor and can be applicable to the next system.

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